THERMAL MANAGEMENT IN THE DESIGN PROCESS OF MV GIS

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ABSTRACT

In this paper we show some of the considerations for thermal design of medium voltage gas insulated switchgears (MV GIS), with reference to one of our late products. There, a consistent design was targeted, which covered ratings up to 2500 A. It is interesting to note, that before any drawing was created, the thermal concept of the new switchgear was at the heart of the very first steps of the design. The interaction between numerical simulation and physical testing is presented. Testing was not only necessary to verify models, but, conversely, input from numerical analysis helped to better understand the testing conditions and to analyze the test results.

INTRODUCTION

As with any electrical device, thermal management of MV switchgear is important to balance the Joule losses by cooling, in order to avoid excessive heating and to assure safe operation. The thermal limits for MV devices are defined by the IEC standard 62271-1 *[1]*.

At present there appears to be a trend towards increased power density. Market is asking more often for equipment with higher current ratings at even more compact dimensions of the devices and at low cost. In practice, especially with current ratings exceeding 1000 A, thermal management turns out to be one of the most important design challenges, along with dielectric design, short ciruit withstand, and others. In the example presented here, we faced such challenge.

Figure 1 shows the cut-open view of a GMAefficient panel [2] with labels indicating its functional elements. Based on the main figures of a switchgear, designed for up to 1250 A at 24 kV, a design of the new device was requested to cover the current range up to 2500 A. Consequently, already at the early concept phase, thermal balances were considered as most determining feasibility criteria. Existing in-house solutions for the different functional elements were analyzed for their power losses at the targeted ratings. First calculations on conceptual functional arrangements were performed, to identify potential solution candidates. Gross-power balance calculations were used to see, if the installed power loss can be balanced by the cooling capacity of the exterior faces, at that time only determined by the targeted over-all dimensions.

It was found, that thermal balance can be achieved with natural convection cooling by extending the effective cooling surface by use of heat sinks. Of course, reduction of installed losses was in the focus as well. But while conductors can easily be dimensioned for thermal balance, concentrated heat sources can only be cooled by these conductors or additional heat sinks. Such concentrated sources are bolted joints of conductors, the movable contacts of a disconnector, and the vacuum circuit breaker (VCB). At the same time lower temperature rise limits (65 K) apply for the disconnector than for any other current carrying conductor joint. This means, that the disconnector is usually one of the most critical components with respect to thermal design.

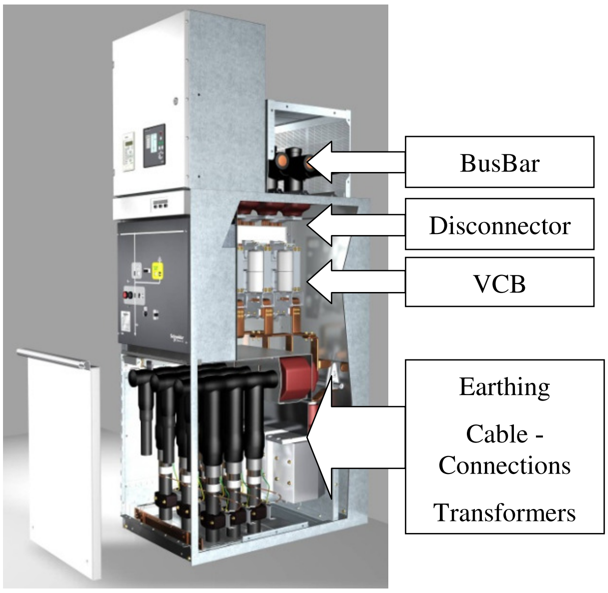

Figure 1: MV GIS and its primary functional units

THERMAL NETWORK METHOD (TNM)

Based on the first gross evaluations, more detailed thermal network calculations were performed. The total power balance for the estimated cooling surfaces at the given gas tank dimensions, considering additional heat sinks, was confirmed. For functional elements and generic parts, like conductors or vacuum interrupters, we could benefit from the verified models in our thermal network library, which was built up during development of earlier products. A raw thermal network model could be created, using generic parts and functional assemblies. In consequence, much more detailed information on the impact of individual parts, temperature distribution and impact by the conceptual arrangement of functions was received from the thermal network calculations. Eventually, the required design parameters were obtained. This was a major step in approving feasibility of the marketing specifications and opened the definition of the product specifications and, eventually, to start the actual design of the product.

It is interesting to note, that the basic thermal concept of new switchgear was developed before any drawing was created. This is of importance, since options for design changes become limited in the course of design due to the growing number of constraints. As soon as the design team created first drafts, more accurate thermal simulation could be performed. At these stages we are able to tell, if the design was already appropriate, or if improvements were still necessary to reach the specifications. With the help of thermal network simulation it was possible to quickly compare different design solutions, giving the project management a better quantitative background for decisions, based on technical performance versus economical footprint and impact on assembly.

Accuracy of TNM

When comparing test results with simulation, we find that the initial simulations got as close as 6 % to the real temperature rise, depending on maturity of assumptions for a design to be tested later. After refining the simulation model according to the actual design and verifications by testing, we finally reached 2 % temperature deviation between simulation and measured values. Once the geometry and materials are known, it is rather straight forward to model interior parts of a gas insulated switchgear (GIS) with high accuracy. For the gross power balance use of average contact resistance values from experience was sufficient. For typical bolted connection of copper parts in MV GIS, the contact resistance is approximately 0.5 μOhm, depending on factors like contact force, number of bolts, shape of contact parts, size of contact surface, surface treatment etc.[3]. Since losses scale approximately with the square of current, it is difficult to thermally balance higher contact resistances then the mentioned values, especially for current ratings like 2500 A.

By all its benefits, the TNM method cannot calculate the flow field of gases. While this does impact less the heat balance inside the GIS, it can be problematic for the balance to ambient. For example, heated air venting from the cable compartment will rise outside the circuit breaker tank. The reference temperature at the walls is therefore increased with respect to ambient temperature, up to 20%. We usually prefer to measure air and gas temperatures during testing and to use a parameter in the TNM, which will be verified against test values. Better prediction from scratch is subject to ongoing development of our calculation tools.

CROSS VERIFICATION OF SIMULATION AND TESTING

One important topic in thermal management is to analyse the test results systematically and improve constantly the simulation models. The measured temperature values and the measured conductor resistances are compared with the calculated values.

Especially for critical parts, like disconnector components, accurate modelling is important. To our experience, it pays off to increase the degree of geometrical resolution even in a TNM. On one hand it means extra work to discretize all the parts "manually", but on the other hand, one gets a better understanding about the paths of heat dissipation as well as weak points in the design. Finally due to this extra discretization work a good matching with test can be achieved.

Ohmic resistance

An example of this cross verification approach is the accurate calculation of the power losses in the switchgear. It was shown in [4], that the skin effect has to be considered carefully. While we do employ FEM, to calculate the a.c. current distribution conducting parts and to obtain their a.c. losses, which are not apparent from d.c. resistant measurements, we want to focus in this paper first to a more basic approach.

The most basic analysis is to compare the losses of the individual components, to get a first clue on where potential improvements can be achieved. The vacuum-circuit-creaker (VCB) section has the highest ohmic loss inside the switchgear. In vacuum there is no convective heat transfer and radiation heat transfer from the contact system of the VCB is low, so most of the power losses of the VCB can only be dissipated through thermal conduction to conductors outside of the interrupter. Improving these connections still allowed for reducing the "hot-spot". For the following figure the VCB resistance is taken as the 100% level to compare with.

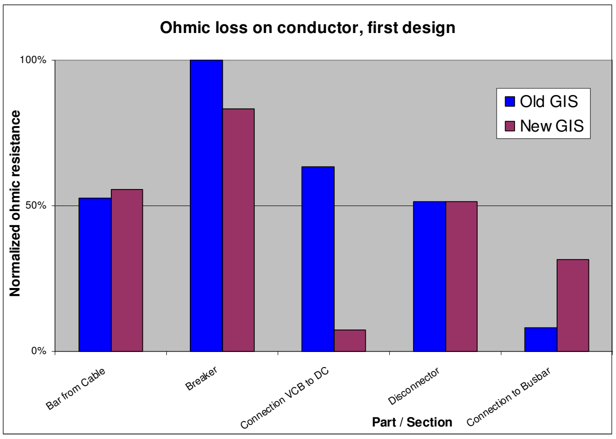

Figure 2: Ohmic loss improvement for a 2500A panel (early design)

Figure 2 illustrates the improvements in ohmic resistance due to re-design and rearrangement for the main components in the conductor path for the new 2500A GIS panel as compared to earlier GIS product design.

Apparently the early design of the connection from the disconnector to the busbar system was sub-optimum. That called for re-design even more since we decided on a solid insulated busbar (SIB) in air. So there was short distance between the disconnector to a bushing through the gas tank and the busbar, where there was little chance to dissipate the power loss.

Improvement process of parts

In Figure 3 the original and the optimized design for a copper-cast disconnector contact is shown. The improvement was first confirmed through a 3-D electromagnetic FEM simulation and later on verified by testing.

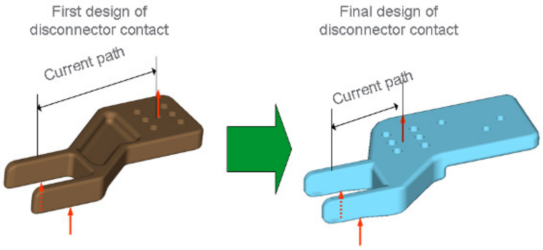

Figure 3: Design improvement of copper castings

A reduction of the ohmic resistance by 1.7 µOhm was achieved and sufficient cooling surface was provided, which lowered the local temperature rise by 5 K. For a 2500 A rated panel this reduction allowed for an increased current load of roughly 125 A. This strong improvement then justified the consequent severe design changes. As can be seen, the location of the bushing had to be shifted and the busbar sectioning had to be adapted for the change. The final optimum had to be found between lowest possible resistance and lowest possible cost impact of the busbar sectioning.

AFLR AIR DUCT DESIGN

Design for personal safety against internal arc is impacting thermal design the most, when accessibility from the rear (AFLR) is required. Then an additional compartment separates the circuit breaker tank from the ambient, meaning a thermal resistance for cooling. Such a duct can cause a temperature rise of up to 16 % for a 2500 A panel, depending on the actual switchgear design. The most problematic part is to provide a sufficient flow of cooling air through the unit. But even when maximizing the air flow through the AFLR air duct, a duct will still introduce resistance by hindering radiative heat transfer as well as by restricting the air flow rate. Thermal radiation can be improved by painting the channel walls for higher emissivity, but care must be taken to keep surface temperature at the accepted level for workers safety. Also in the case presented here, the duct required additional improvements of the circuit breaker (CB) unit itself, as compared to the AFL design, to allow for keeping nominal rating of the GIS.

A simplified drawing of a panel seen from the side is shown in Figure 4, indicating the directions of air flow through the AFLR air duct and between the single panels. An air inlet is located at the bottom on the rear side, outlets on the top. The openings are equipped with flaps, which will close in case of an internal arc.

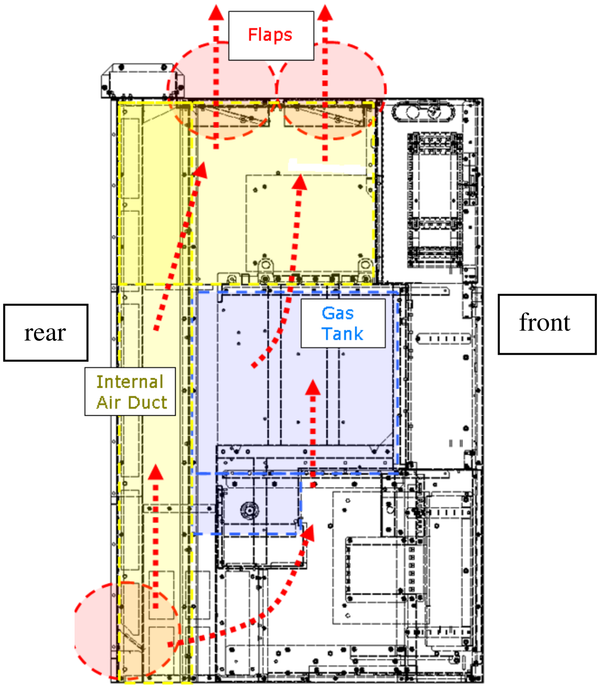

Figure 4: Air flow through an AFLR air duct

The placement of the openings allows for development of the stack effect. Although the calculation using TNM could already provide decent precision, the CFD method allowed for a more detailed view on the air flow.

Figure 5 shows the result of such a CFD analysis. Shown here is a view of the entire geometry of the air duct and the result plots offset for better visibility. Temperature profile is depicted in the contour graph while the air flow is indicated by a vector plot.

After numerous analyzes and subsequent optimizations of the air duct design, a thermal network model could be verified. The principle of the model is shown in a schematic in Figure 6. Cold air is entering the duct close to the floor. In simulation inlet temperature had to be corrected according to measurement to a value lower than the average ambient temperature. Heat flows from the enclosure of the circuit breaker unit to the rear air duct and by convection to the busbar channel above, which will be at elevated temperature. There, buoyancy will vent the hot air through the top flap opening. The AFLR air duct connects panels by openings and allows for air flow from the most heated panel to cooler adjacent ones. Resistors marked as “left and right unit heat flux” respect the flow and radiative heat transfer between units. Straight forward modelling of the air flow using mass flow elements only did not show reasonable results in our TNM. We had do approximate heat fluxes by use of simple resistances. Improvement of the mass flow elements is still needed.

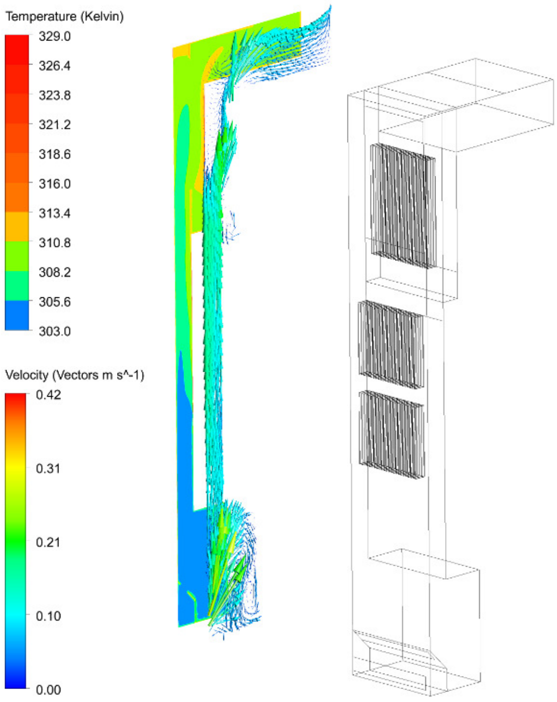

Figure 5: Temperature distribution and air velocity profile inside the air duct

Figure 7 shows the result of the TNM for a AFLR in comparison to the AFL results. The additional thermal resistances introduced by the duct, basically shifts the temperature at each measurement points upwards.

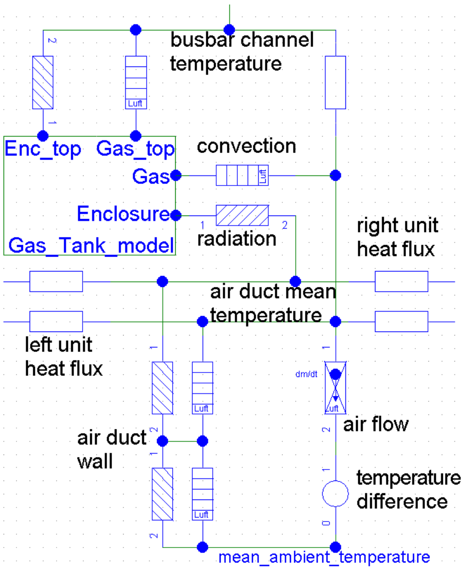

Figure 6: Thermal network model of an AFLR air duct

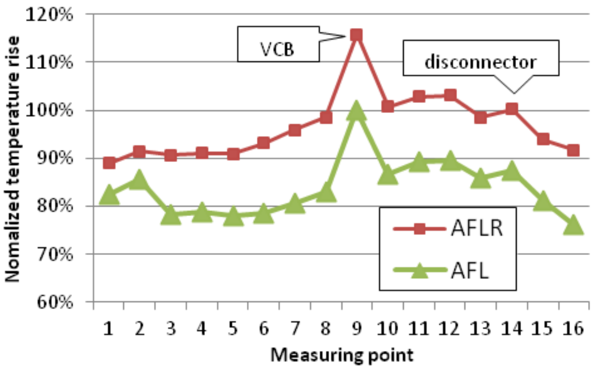

Figure 7: Temperature profile comparison of the 2500 A panels, AFLR and AFL

CONCLUSION

Thermal management is a key competency in design of MV GIS, which must be utilized from the early conceptual design stage and continuously accompany the design process. Failing to employ thermal analysis for high power switchgear in the early stage will most likely require a complete re-design in a late design period and delay product release unpredictably. While the process and calculation models do still need more improvements to enable a better prediction of performance from scratch, our experiences show, that precise results can be obtained at a moderate simulation effort by employing TNM. Complementing TNM with detail analyses by more sophisticated methods like CFD and FEM enables precise results of large and complex systems. The time to come from ideas to design solutions with quantitative conclusions that support a strategic design can be drastically reduced, as compared to a try-and-error approach by physical testing. Since TNM is not a “black box” approach, a deeper understanding of thermal balances becomes accessible for the development and testing teams. Carefully validated models of single components and entire panels allow for prediction of the influence of neighbouring panels far before a type test is being planned. This way, each step in even early design process allows for a successive assessment of the final product performance.

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